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HEAVY-FOG REGIONS IN THE CONTERMINOUS UNITED STATES [1]

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ABSTRACT

The heavy-fog statistics for 256 first-order weather stations were utilized to update analyses of the geographic distribution of fog within the conterminous United States. The survey shows that heavy fog (visibility one-fourth mile or less) occurs more than 20 days a year at approximately 50 percent of the first-order weather stations (of which 229 are air terminals) and that the mean heavy-fog frequency reported per station appears to be generally higher than it was 30 yr ago. The geographic distribution of heavy fog is shown in two ways—by a conventional isopleth analysis and by fog climatic regions with characteristic frequency distributions.

1. INTRODUCTION

There is periodic need for knowledge of the frequency distribution of heavy fog at air terminals in the United States. A survey of the literature in 1964 revealed some old or simplified fog-frequency distributions (Ward, 1925, Stone, 1936, U.S. Department of Agriculture, 1941, and Haurwitz and Austin, 1944) and distributions of fog by type or mechanism (Stone, 1936, Byers, 1959) but no reasonably current, detailed, quantitative fog-frequency analysis.[3] This lack motivated a brief climatological study and the summary presented here.

The first fog-frequency distribution produced was a conventional isopleth analysis such as those that have been published in the past. This provided a basis of comparison with older studies, but such analyses can be misleading. Fog is largely a localized weather phenomenon and the natural station-to-station frequency variation in some areas requires subjective analysis.

Study of the isopleth analysis reveals that the United States can be divided into regions of reasonably common terrain and geographic properties that are strongly related to fog frequency. The conterminous United States has been divided into seven such regions and the heavy-fog frequency distribution for each provides an essentially objective insight into the frequency distribution of heavy fog at air terminals.

2. DATA BASE AND PERIOD OF RECORD CONSIDERATION

The source of data for this study was the U.S. Weather Bureau, *Local Climatological Data* summaries for 256 first-order weather stations in the conterminous United States. The basic fog statistics used were the mean annual number of days with heavy fog as reported in the 1963 annual summaries.[4] These statistics are based upon the total length of record at each station and represent widely differing numbers of years of observation and often a number of different locations in or near a given city. Some stations have as few as 2 yr of record, while the frequencies of heavy fog for other stations are based upon as many as 60 to 80 yr of observations. A few stations had long records for earlier years, but a substantial change in station location reduced the record to 10 yr or less as of 1963. Earlier data were acquired for these stations and compared with the more current, shorter period statistics. In most instances where such a double record was available, the long-period statistics indicate fewer days with heavy fog than do those of the more recent, shorter period. Table 1 shows the comparison between long- and short-

TABLE 1.—*Comparison between long- and short-term heavy-fog frequency*

Station	Mean annual heavy-fog frequency (days/yr)	Period of record (yr)	Mean annual heavy-fog frequency (days/yr)	Period of record (yr)
Tallahassee, Fla.	55	2	41	22
Lake Charles, La.	51	2	37	23
Lansing, Mich.	24	9	13	45
Rochester, Minn.	38	3	16	11
Saint Louis, Mo.	10	6	8	22
Lincoln, Nebr.	7	8	5	58
Atlantic City, N.J.	43	5	21	53
Williston, N. Dak.	9	2	7	45
Toledo, Ohio	20	8	8	83
Fort Worth, Tex.	10	10	8	55
Alpena, Mich.	18	4	20	45
Glasgow, Mont.	11	8	12	18
Havre, Mont.	5	3	5	56
Victoria, Tex.	24	2	28	14

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[3] Since this work was performed a new fog-frequency distribution has been published by Court (1966).

[4] In these summaries a day with heavy fog is any day when the prevailing visibility was reduced to one-fourth mile or less by fog for one or more observations. If other obscuring phenomena were occurring simultaneously, the contribution of fog was a matter of observer judgment.

term mean heavy-fog frequency for the 14 stations for which such data were available.

Although there are several possible explanations for the difference between more current and older means—e.g., changes in observing procedure, climatic change, increased industrialization, changes in airport or observation sites—the available data were not sufficient to ascertain the true cause. However, the mere existence of these differences, coupled with the wide variation in record length for the 256 stations used in the analysis, does suggest that length of record may contribute to differences in recorded fog frequency between stations in a given area.

Separation of this effect and that of local environment differences is difficult or impossible where two stations in close proximity have substantial differences both in length of record and in reported fog frequency. For example, only 23 mi separate two Detroit, Mich., stations having 5 and 30 yr of record and mean annual heavy-fog frequencies of 25 and 12 days, respectively. Toledo, Ohio's 83-yr record (table 1) represents five city and two airport locations as much as 9 mi apart. The 8-yr record began with a move of only 15 mi. The substantial change in heavy-fog frequency at Toledo could be due either to different periods of record or to different locations, or both. Because of such uncertainty, the fog frequency used in the analysis for the stations in table 1 was that which most closely agreed with adjacent stations.

3. ISOPLETH ANALYSIS

By nature, fog is largely a localized weather phenomenon because the causative factors of moisture and cooling are greatly influenced by local terrain and geography. Nevertheless, large geographical areas are sufficiently uniform in character to allow a continuous analysis of fog-frequency distribution for the density of reporting stations in most parts of the United States. Figure 1 is such a conventional isopleth analysis of annual heavy-fog frequency. It was drawn as objectively as possible to all 256 stations for which data were available. The solid isopleths were drawn to constant 10-day increments up to 100 days so that frequency gradients and singularities are evident. The most notable exceptions to a continuous distribution are the obvious discontinuities indicated by steep gradients along the Sierra Nevada Mountains and the central Appalachian Mountains, the singularities at some coastal stations such as New Orleans, La., Point Mugu, Calif., Duluth, Minn., and Nantucket, Mass., and some mountain stations such as Mt. Washington, N.H., and Stampede Pass, Wash.

Most of the area east of the Sierra Nevada and Cascade Mountains and west of the Tennessee Valley can be analyzed in greater detail without appreciable degeneration of the pattern. On the other hand, along the Pacific coast and in the central Appalachians fog is such a localized phenomenon that with the station density available even the 10-day frequency isopleths cannot be located with certainty.

Figure 2 is the dense-fog frequency analysis published by Stone (1936) for data through 1931 or 1932. (Dense fog was defined as a fog that restricted visibility to 1,000 ft or less in contrast to the one-fourth-mile (1,320 ft) criteria presently used for heavy fog.) Relatively few of the stations in figure 1 had more than 30 yr of record in 1963. So, Stone's analysis and figure 1 were essentially drawn for mutually exclusive data. A comparison of the two patterns shows that both have similar basic features, but the current analysis displays a 10- to 20-day higher overall fog frequency everywhere except in the dry Great Basin region. Such an increase is also evident in a comparison of the fog-frequency distribution presented in "Climate and Man" (U.S. Department of Agriculture, 1941) for data through 1938 with the distribution published by Court and Gerston (1966) for data through 1960. The Court and Gerston analysis in turn shows essentially the same frequency distribution as that in figure 1. This general increase in fog frequency lends support to the frequency increases found at most of the individual stations in table 1. It also supports the suspicion that at least some of the station-to-station fog-frequency differences are due to variable lengths of station records.

4. REGIONAL ANALYSIS

Isopleth analysis is founded on the assumption that the analyzed variable is continuously distributed in space. Although such analysis is often used to describe a smoothed distribution of a variable that is not continuously distributed, the greater the unorganized variation of the analyzed parameter the more subjective and less meaningful is such an analysis. When the natural station-to-station variability of heavy-fog frequency is compounded by variable lengths of record covering a period of basic frequency change, an isopleth analysis can be very misleading in certain regions of the United States. Because of this, other means of displaying the data were explored.

As different types of analyses were tried, it became evident that the United States could be divided into seven regions of reasonably common terrain and geographic properties that are strongly related to fog frequency. Figure 3 shows the boundaries of these regions and the individual heavy-fog frequency for all 256 stations used in the study. The boundaries are drawn where there is a change in the basic fog-frequency distribution as indicated by either a strong gradient of frequency or a distinct change in gradient. As would be expected, the boundaries between some frequency regimes coincide approximately with orographic features such as the Sierra Nevada and Cascade Mountains, the Continental Divide, and the foothills of the Appalachian Mountains. Others appear to represent the limits of influence of large bodies of water. But in every case the criterion for drawing a boundary was the heavy-fog-frequency distribution and only minor adjustments were made to agree with geographic features.

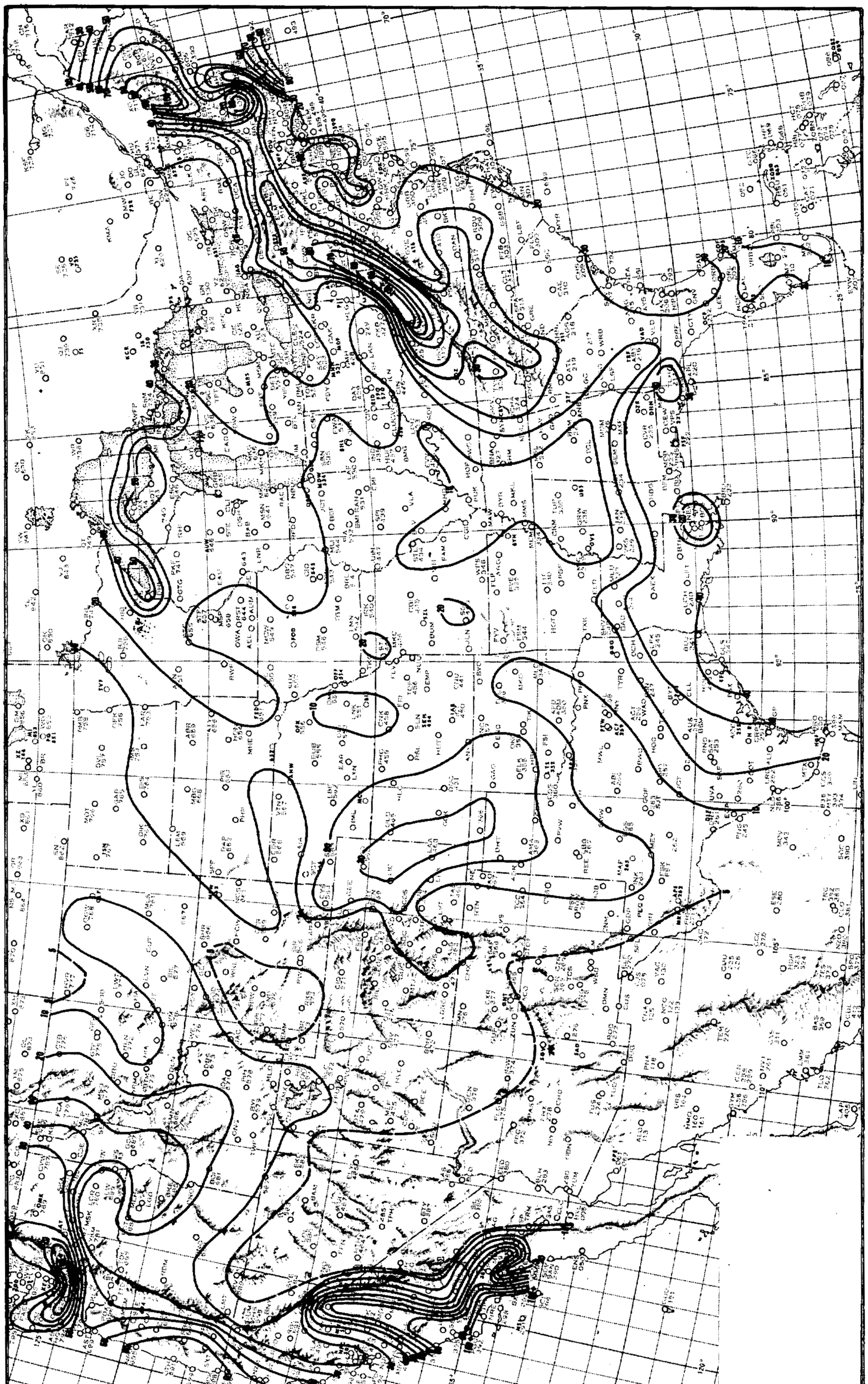

FIGURE 1.—Mean annual heavy-fog frequency (days/year). The isopleths show the man annual number of days with fogs that reduced visibility to one-fourth mile or less. The dashed isopleths represent intermediate 5-day-interval frequencies in regions of weak frequency gradient.

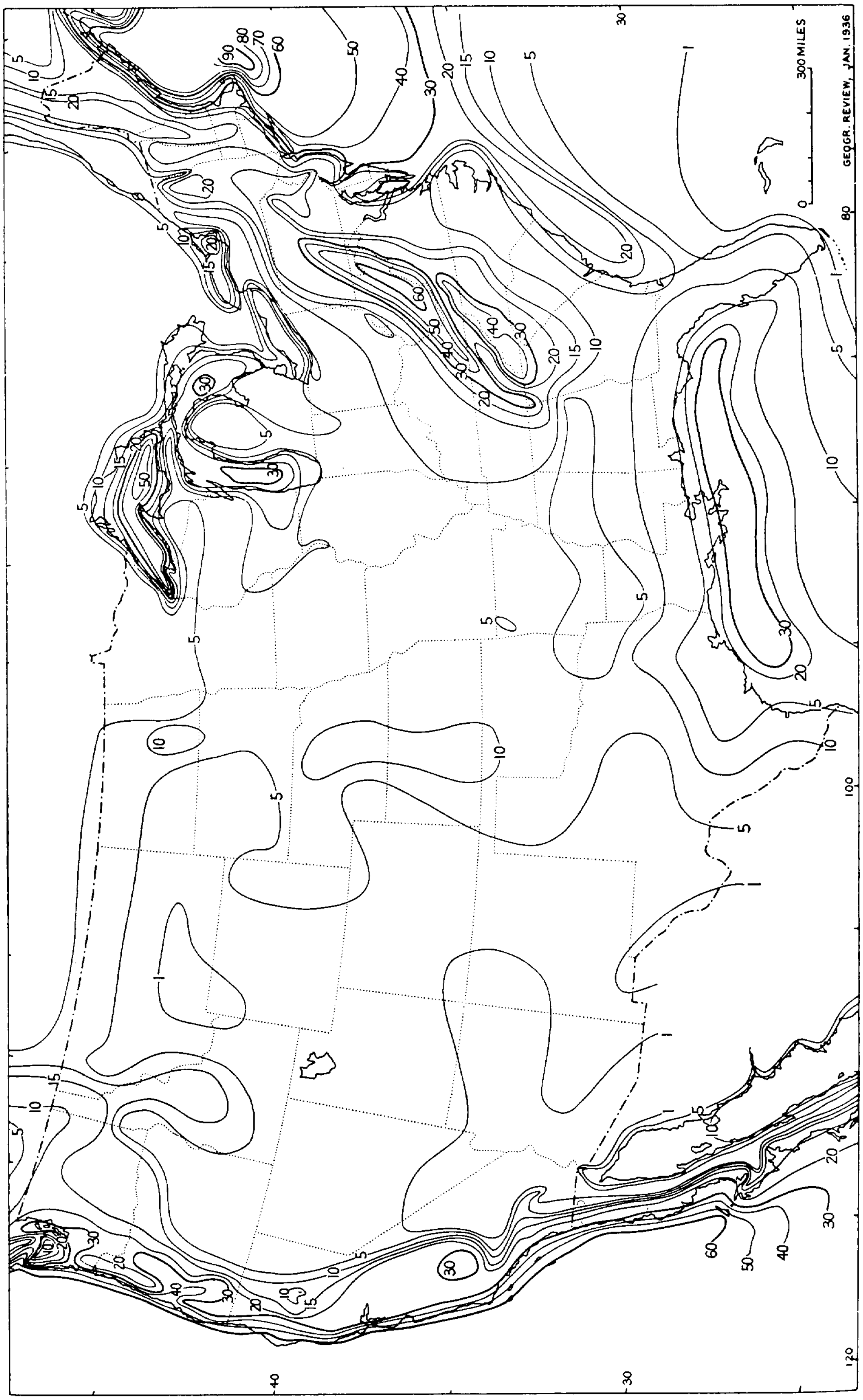

FIGURE 2.—Map showing the distribution of fog in the United States published by Stone (1936). The isopleths show the mean annual number of days with "dense fog, i.e. fogs obscuring the visibility to 1,000 ft or less" based upon records up through 1931 or 1932.

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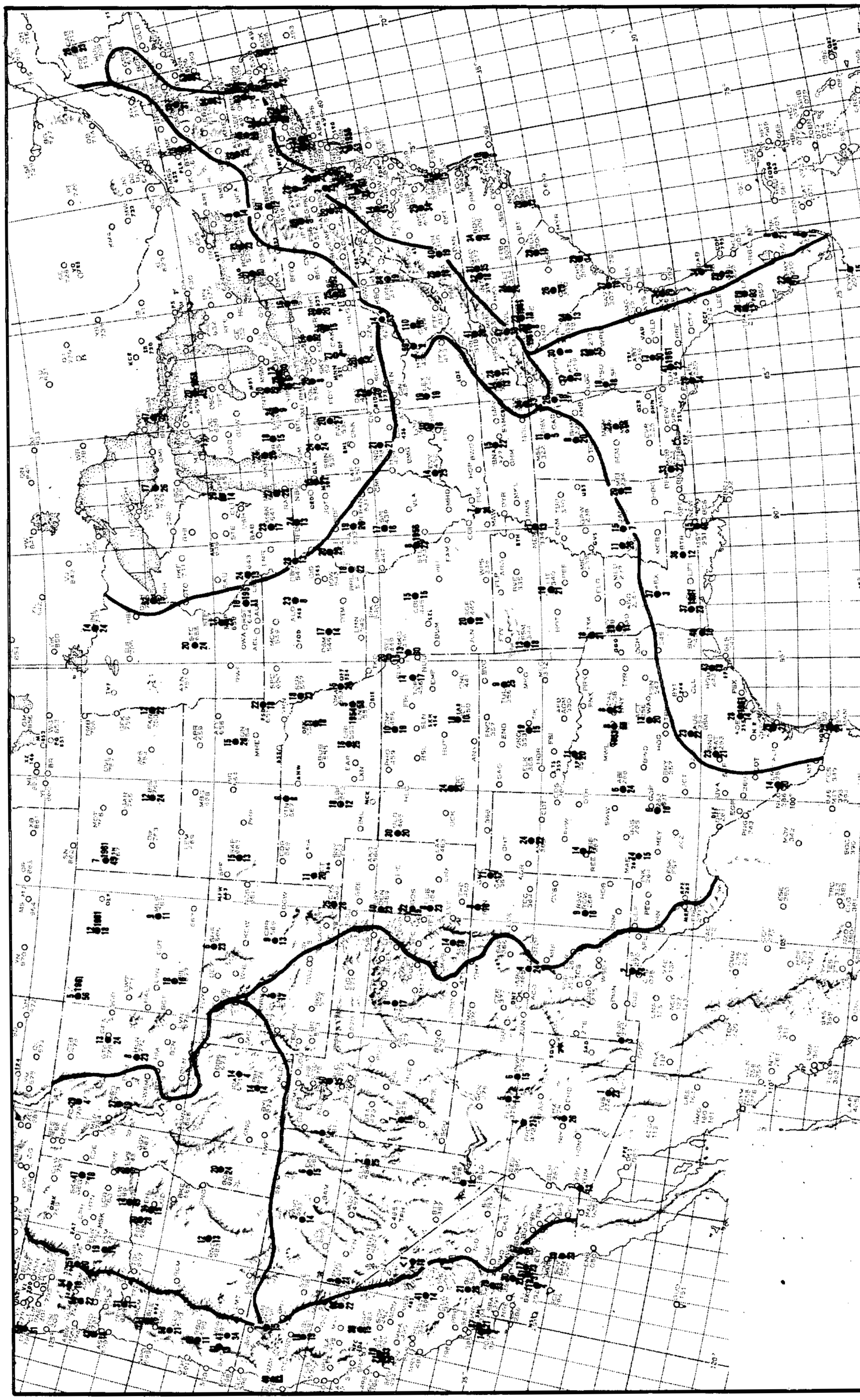

FIGURE 3.—Boundaries of fog climatic regions and station-frequency data. The boundaries shown delineate the regions for which the histograms of figures 4 through 6 were drawn. The number above each station dot is the annual heavy-fog frequency for the period of record displayed below the station dot. If the last year of record is other than 1963, the actual year is shown to the right or left of the station location.

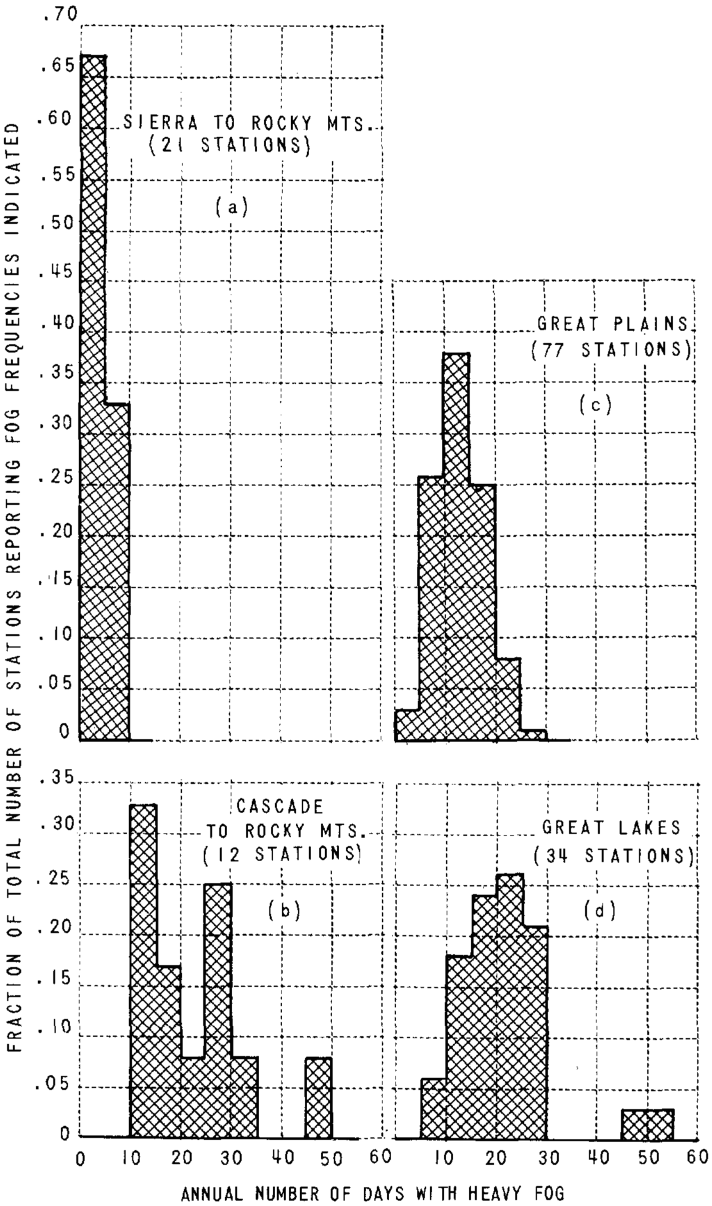

FIGURE 4.—The histograms of fog frequency for four of the fog climatic regions delineated in figure 3.

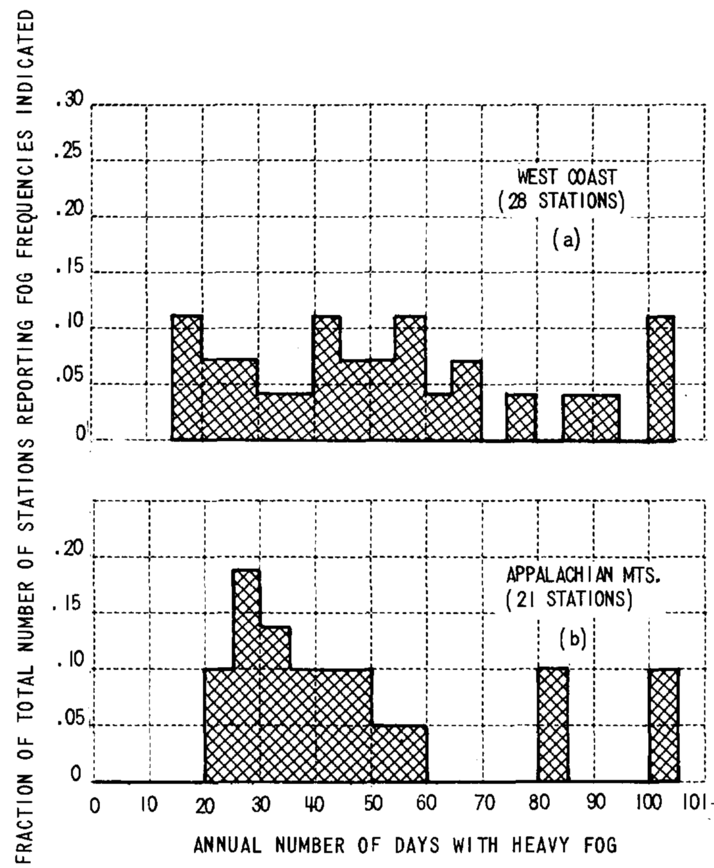

FIGURE 5.—The histograms of fog frequency for two of the fog climatic regions delineated in figure 3.

Data were grouped according to the areas in figure 3 and histograms showing the percentage of stations reporting heavy fog of given frequency were plotted for each area. These histograms and one covering the entire conterminous United States are presented in figures 4 through 7. To the extent that the reporting stations are representative of their regions, the figures may be interpreted as the fraction of the total area of a region that is characterized by the given fog frequencies.

A brief description of the fog characteristics of each region is given below.

SIERRA NEVADA TO THE ROCKY MOUNTAINS

This arid region is cut off from moisture by mountain barriers both east and west. The lack of moisture causes a narrow, uniformly low fog-frequency distribution (fig. 4a). No station in this region averages over 10 days of heavy fog per year, while the majority experience 5 days or less per year.

CASCADE TO THE ROCKY MOUNTAINS

This area is characterized by mountains separated by broad, flat valleys. Moisture, though not abundant, is adequately supplied from modest precipitation. As a result, all stations in this region experience an average of at least 11 days of heavy fog per year, but only two experience more than 30 days per year (fig. 4b).

GREAT PLAINS AND MISSISSIPPI VALLEY

The uniform terrain and limited moisture characteristics of this extensive region are responsible for the narrow, moderate, heavy-fog-frequency distribution displayed in figure 4c. The principal water source is the Gulf of Mexico; no other large water bodies directly influence fog formation in this area. Orographic effects associated with the foothills of the Rocky Mountains tend to broaden the frequency distribution in that area, and five of the seven stations reporting over 20 days of heavy fog per year are located along the eastern slopes of the mountains.

GREAT LAKES AREA

The influence of the Great Lakes extends south and west of the lakes to an ill-defined border with the Great Plains and Mississippi Valley; to the east the Appalachians form

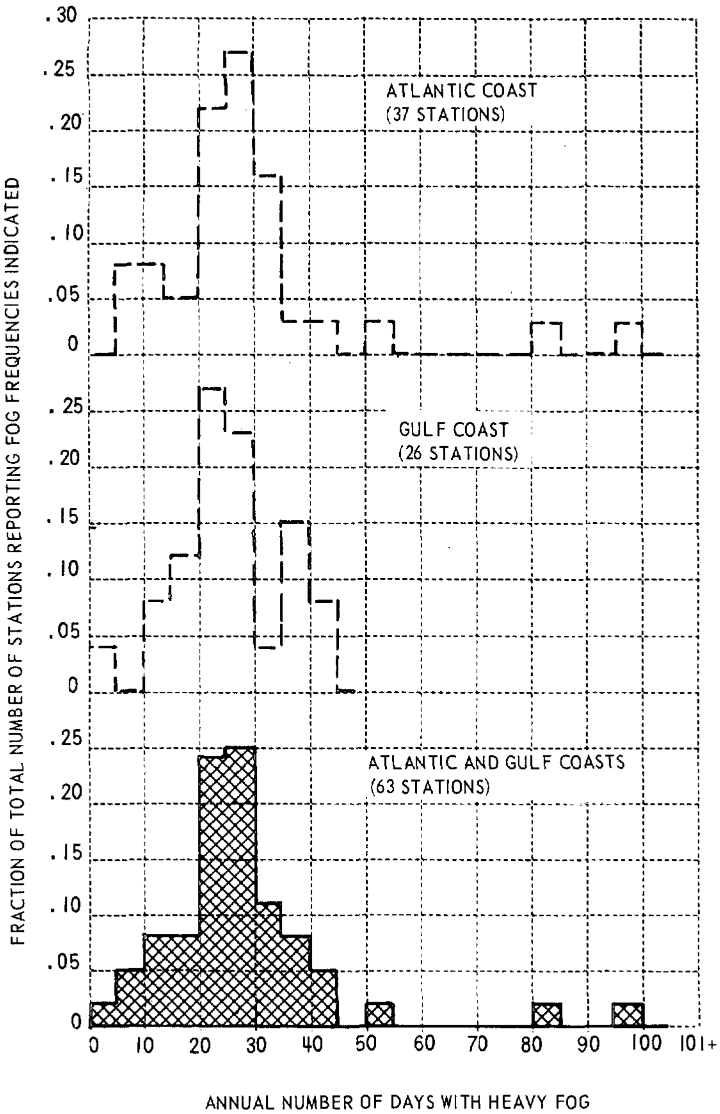

FIGURE 6.—The histograms for the Atlantic and Gulf Coast regions delineated in figure 3, and the combined histogram for the two regions.

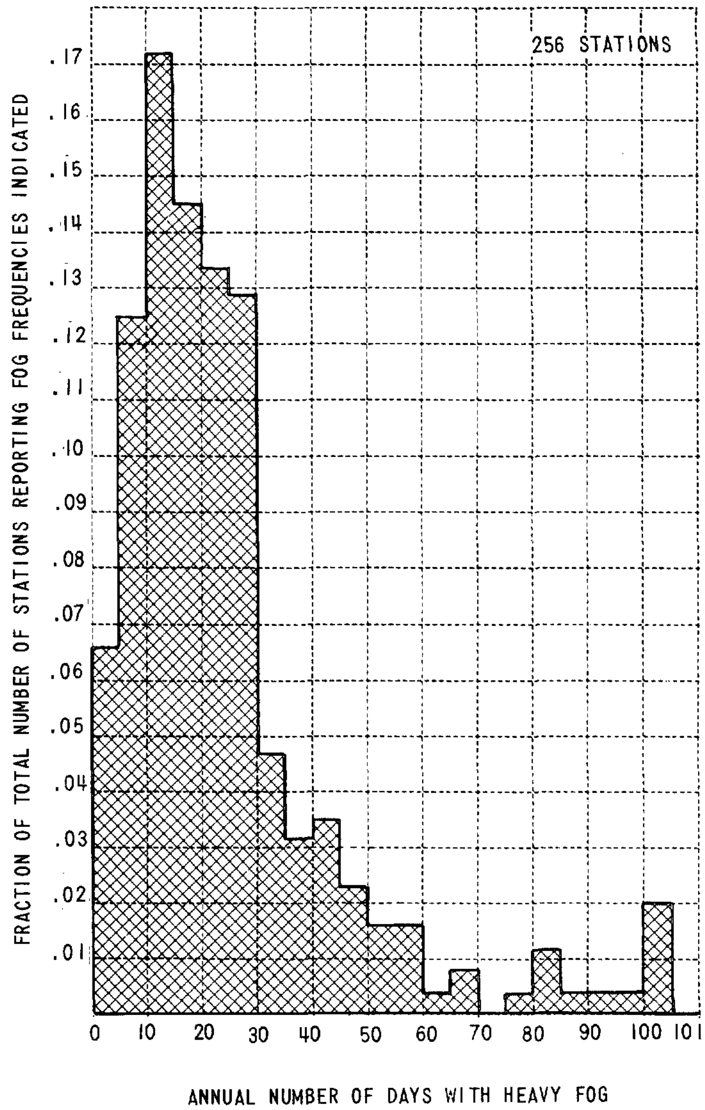

Figure 7.—The combined histogram for the conterminous United States.

a more distinct border. Heavy fog is understandably higher near the Great Lakes than on the Great Plains, and the spread of fog frequencies is also greater in this area (fig. 4d). The highest fog frequencies are near the water, but fog frequency does not vary as much with distance from the water as it does among stations at comparable distances from water (fig. 3).

WEST COAST

The area west of the Sierra Nevada and Cascade Mountains is under the influence of the Pacific Ocean and the orographic lift provided by the mountains. As a consequence, heavy-fog frequency is generally high while the irregular terrain and varying proximity of reporting stations to the ocean cause a wide spread in frequencies (fig. 5a). The greatest frequencies occur along the coast of southern California and at the stations located high in the mountains, as would be expected. But much of the spread is due to the inclusion of mountain stations such as Stampede Pass, Wash. (altitude 3,958 ft, frequency 251 days/yr). At such stations the statistics represent low cloud base at or below station elevation more often than fog in the more conventional sense. However, such surface obscurations fall within the USWB and WMO definition of fog, so they have been included in the analyses and frequency distributions.

APPALACHIAN MOUNTAINS

The Appalachian Mountains region resembles the West Coast region in many ways. Both represent areas of irregular terrain and substantial moisture together with orographic lift. As a result, the fog-frequency distributions in the two regions are very similar, both showing high average incidence and large frequency spread (fig. 5b). But the Appalachian Mountains region exhibits a more distinct peak (from 25 to 30 days) not found on the West Coast. The annual number of days with heavy fog in the

Appalachians varies from a low of 22 days to a high of 307 days. (The latter actually represents primarily low cloud occurrence at Mt. Washington.) In general, the greatest fog frequency is found to the west of the highest terrain and is due to orographic lift of predominantly westerly winds.

ATLANTIC AND GULF COASTS

These two coastal regions were at first treated separately, but because of the strong similarity of their fog-frequency distributions they have been combined into a single region (fig. 6). Both coasts display a moderately broad frequency distribution around a relatively high modal frequency. However, despite the wide variation in the proximity of stations to large bodies of water, the frequency spread is substantially less than that of either the Appalachian Mountain region or the West Coast areas—where irregular terrain creates more widely diverse, localized fog-producing conditions. The one extreme local influence in this area is found in the Nantucket-Block Island area where the heavy-fog frequency is about twice that of the other stations along these coasts.

5. CONCLUSIONS

The regional histograms provide insight into both the variations of heavy-fog frequency from one point of the Country to another and the variability of frequencies within each region. However, they represent the spatial distribution of fog frequencies only to the extent that reporting stations are representatively distributed within a region. This is not a restriction to interpretation of the histograms in terms of the frequency distribution of heavy fog at air terminals, since most of the observations were made at air terminals.

When all regions are combined into a single histogram of fog frequency (fig. 7), the significance of fog as an air-terminal hazard becomes apparent. Approximately 50 percent of the reporting stations (229 of the 256 represent air terminals) experience over 20 days per year with periods of one-fourth-mile visibility or less. Most of the extremely high frequency reports come from stations that are not air terminals, but the majority of the 244 stations reporting up to 70 days with heavy fogs are air terminals.

REFERENCES

Byers, H. R., *General Meteorology*, McGraw-Hill Book Co., Inc., New York, **1959**, 540 pp. (see p. 491).

Court, A., and Gerston, R. D. "Fog Frequency in the United States," *The Geographical Review*, Vol. 56, No. 4, Oct. **1966**, pp. 543–550.

Haurwitz, B., and Austin, J. M., *Climatology*, McGraw-Hill Book Co., Inc., New York, **1944**, 410 pp. (see Plates 12 and 13).

Stone, R. G., "Fog in the United States and Adjacent Regions," *The Geographical Review*, Vol. 26, No. 1, Jan. **1936**, pp. 111–134.

U.S. Department of Agriculture, "Climate and Man," *Yearbook of Agriculture, 1941*, Washington, D.C., **1941**, p. 737.

Ward, R. D., *The Climates of the United States*, Ginn and Co., Boston, **1925**, pp. 335—338.

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CORRECTION NOTICE

Vol. 96, No. 1, Jan. 1968: p. 26, 2d paragraph, 3d line from bottom, F is to be read instead of E, and G instead of F; p. 28, 3d line after equation (4) $\bar{u}_g$ instead of u_g, and 10th line after equation (4), release instead of reaseel; p. 30, fig. 11 caption, $[\bar{u}][\bar{v}]$ instead of $[u]$ $[v]$.